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Recent experimental progress on the charmoniumlike states[☆]

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Abstract

We review the recent experimental progress on the charmoniumlike states, mainly from the e^+e^- annihilation experiments BESIII, Belle, BaBar and CLEO-c, and the hadron collider experiment LHCb. We discuss the results on the production and decay of the X(3872) states, the vector Y states, as well as the charged and neutral charmoniumlike Z_c states.

Keywords:
Charmoniumlike States, Exotic states, Charmonium

1. Introduction

Quantum Chromodynamics (QCD), the fundamental theory of the strong interactions, is well tested at short distances, but is not well understood at long distances, where non-perturbative effects become important. One of the basic properties of QCD is the hadron spectroscopy. The elementary constituents of hadrons are quarks, antiquarks, and a vector SU(3) color force between quarks and antiquarks mediated by an octet of gluons. Quarkonium spectroscopy is a ideal system to investigate and understand QCD. In theory, because the heavy-quark mass provides a natural boundary between the perturbative and nonperturbative regimes, quarkonium system provides a unique laboratory to understand the interplay between perturbative and nonperturbative effects in QCD. The non-relativistic nature of heavy-quarkonium systems allows us to use the powerful effective-field-theory tools to analysis these systems, to unravel the complicated effects of QCD dynamics [1].

Because QCD is confining, only color-singlet hadron states exist in nature. In the conventional quark model, mesons are composed of one quark and one antiquark, while baryons are composed of three quarks [2]. However, QCD allows the existence of glueballs (with no quark), hybrids (with quarks and excited gluon), multi-quark states (with more than three quarks) and hadron molecules (bound state of two or more hadrons), so called exotic states. The existence of the exotic states is a directly test of QCD. In experiment, it is a long history of searching for these exotic states, and many candidates were proposed [3, 4]. However, no solid state was unambiguously identified in the past few decades, until recently, there are some hints on charmoniumlike and bottomniumlike particles.

In the past few decades, for charmonium spectroscopy, all the states below the charm pair threshold in mass are observed experimentally. Also, it is found the observed spectrum are in good agreement with the prediction of charm and anti-charm potential model [5]. However, above charm threshold, there are still many missing states, which need more experimental investigation in future. The most interesting thing is, in the past decade, a lot of new states were observed in the final states with a charmonium and some light hadrons. All these new observed states populate in the charmonium mass region, can be the candidates of un-observed conventional charmonium. However, a number of fea-

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tures of these new states reveal that they are not the conventional mesons [4, 6, 7, 8].

Because of the unprecedented high luminosity and copious production of charm and anticharm quark pair, in the past decade, dramatic progress on the exotic states was achieved by the two B-factories, *i.e.* Belle [9] at KEK and BaBar [10] at SLAC. The BESIII [11] experiment at the BEPCII collider, running in the tau-charm energy region with high luminosity, can provide extreme clean environment to study the charmonium and charmoniumlike states. The LHCb [12] experiment at LHC has accumulated 3 fb^{-1} pp collision data at $\sqrt{s}$ = 7 and 8 TeV, which correspond to more than an order more in magnitude of B decay compared to the two B-factories, can improve the study of the new observation in B decays. In this review, we present the most recent experimental progress on the study of the X(3872) states, the vector Y states, and the charged and neutral charmoniumlike Z_c states *etc*. The results are from the e^+e^- annihilation experiments BESIII, Belle, BaBar and CLEO-c [13], as well as the hadron collider experiment LHCb.

2. X(3782) State

The X(3872) state was first observed by the Belle experiment in the decay $B^{\pm} \to K^{\pm}\pi^+\pi^- J/\psi$ more than ten years ago [14], and then confirmed subsequently by the inclusive production in $p\bar{p}$ collisions by CDF and D0 experiments [15, 16] and by BaBar experiment in the same discovery channel [17]. Since its discovery, the X(3872) state has stimulated special interest for its nature. Theoretically, it has been explained as a loosely bound hadronic molecules, a $\chi_{c2}(2P)$ candidate, a mixture of charmonium and molecule, and other configurations [4]. Experimentally, The observation of the radiative decay mode $\gamma J/\psi$ by Belle, BaBar and LHCb experiments [18, 19, 20] establishes the C-parity as positive. The analysis by the CDF experiment of the $\pi^+\pi^- J/\psi$ decay mode reduce the possible J^{PC} quantum number to be 1^{++} and 2^{-+} [21], and a full five dimensional angular analysis by LHCb on the same decay mode ruled out 2^{-+} by over 8σ compared to 1^{++} [22].

The X(3872) was observed in B decays and hadron collisions only before. Since its quantum number is 1^{++}, it is expected to be produced through the radiative transition of the excited vector charmonium or charmoniumlike states, such as the ψs and Ys. BESIII experiment performed a searching for X(3872) with the process $e^+e^- \to \gamma X(3872) \to \gamma\pi^+\pi^- J/\psi$ by using the 2.9 fb^{-1} of data samples collected at the center-of-mass energy (CME) $\sqrt{s}$ = 4.009, 4.230, 4.260 and 4.360 GeV,

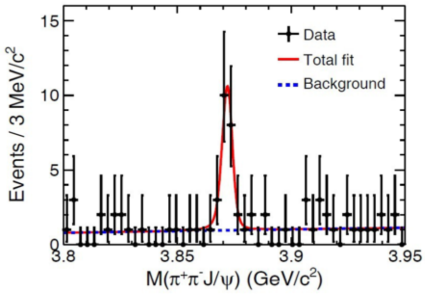

Figure 1: Fit to the invariant mass distribution of $\pi^+\pi^- J/\psi$ (summed over all energy points) measured by BESIII experiment. Dots with error bars are data, the curves are the fit results

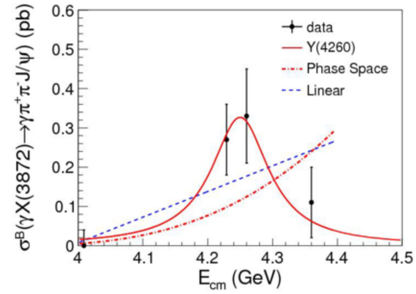

Figure 2: The fit to $\sigma^B(e^+e^- \to \gamma X(3872)) \times B(X(3872) \to \pi^+\pi^- J/\psi)$ as function of CME measured by BESIII with different function. Dots with error bars are data, the curves are the fit results.

where J/ψ is reconstructed with its e^+e^- and $\mu^+\mu^-$ decay modes [23]. The X(3872) signal is observed clearly in $\pi^+\pi^- J/\psi$ invariant mass, as shown in Fig. 1 (summed over all energy points). The measured mass and width are well consistent with the PDG values [24]. The product of the Born cross section times the branching fraction of $X(3872) \to \pi^+\pi^- J/\psi$ as a function of CME are shown in Fig. 2. For the data with $\sqrt{s}$ = 4.009 and 4.360 GeV, the X(3872) signals are not significant, and the upper limit at the 90% confidence level (C.L.) were determined. The measured cross sections at around $\sqrt{s}$ = 4.26 GeV are an order of magnitude higher than that of continuum production by NRQCD calculation [25], and its line shape depend on the CME is consistent with the shape of Y(4260) resonance, which strongly suggest that the observed X(3872) signal might come from the radiative transition of Y(4260), and is a new decay mode of Y(4260) resonance. Taking the cross section of $e^+e^- \to \pi^+\pi^- J/\psi$ measured at $\sqrt{s}$ = 4.26 GeV measured by BESIII experiment [26] and assuming the branching fraction $B(X(3872) \to \pi^+\pi^- J/\psi)$ = 5% [27], the fraction $R = \frac{\sigma^B(e^+e^- \to \gamma X(3872))}{\sigma^B(e^+e^- \to \pi^+\pi^- J/\psi)}$ is about 11%, which is much larger than what we expected, and suggest there might be some commonality in the nature of X(3872) and Y(4260) states.

There are some other properties of X(3872) state observed experimentally, which are very important to investigate and understand its nature. Being near the $D^0\bar{D}^{*0}$ mass threshold and very narrow, the 1^{++} quantum number imply that it has an S-wave coupling to $D\bar{D}^*$, and was interpreted as a good candidate of $D\bar{D}^*$ molecule or a tetraquark state [4]. In its discovery mode $\pi^+\pi^-J/\psi$, the $\pi^+\pi^-$ system is compatible with the decay of a virtual ρ [14], which expects X(3872) has isospin 1. However, in the decay mode of $\pi^+\pi^-\pi^0J/\psi$, the $\pi^+\pi^-\pi^0$ system is compatible with the decay of a virtual ω [28], imply its isopin 0. The observed comparable branching fractions of two decay modes indicate a severe violation of isospin symmetry, which may suggest that X(3872) is the $D\bar{D}^*$ molecule. The radiative transition $X(3872) \to \gamma J/\psi$ was well observed by BaBar, Belle and LHCb experiments [18, 19, 20]. The evidence for the $X(3872) \to \gamma\psi(3686)$ reported by BaBar and LHCb experiments with a statistical significance of 3.5 σ and 4.4 σ [29, 20], respectively, and a upper limit by Belle experiment, results in the ratio of the branching fractions $R = \frac{B(X(3872)\to\gamma\psi(3686))}{B(X(3872)\to\gamma J/\psi)}$ to be 3.4 ± 1.4, $2.46 \pm 0.64 \pm 0.29$ and < 2.1 for three experiments, respectively. The measured values of the ratio does not support a pure $D^0\bar{D}^{*0}$ molecular interpretation of X(3872), but agrees with expectations for a pure charmonium interpretation of the X(3872) state and a mixture of a molecule and a charmonium interpretation [4, 20].

3. Y States

Y states, neutral vector charmoniumlike particle, which have quantum number 1^{--}, can be directly formed in a e^+e^- collision. In the past decade, two B factories have been proven to be very fruitful on the Y states via Initial State Radiative (ISR) process. Several Y states, spanning a range of masses between 3900 and 4700 MeV, were observed in dipion transitions to either J/ψ or $\psi(3686)$.

3.1. Y states observed in $\pi^+\pi^-J/\psi$ final states

The most well established of these states, the Y(4260), was first observed by BaBar experiment [30] in the ISR process $e^+e^- \to \gamma_{ISR}\pi^+\pi^-J/\psi$, and subsequently confirmed by Belle and CLEO experiments in the same process [31, 32]. Beside Y(4260), Belle experiment also reported a additional broad structure, named Y(4008). Recently, both Belle and Babar experiments updated the results of the same analysis $e^+e^- \to \gamma_{ISR}\pi^+\pi^-J/\psi$ with their full data sets, respectively. [34, 33]. With 967 pb^{-1} of data sample collected at $\Upsilon(nS)$ (n=1, 2, $\cdots$ 5) resonances, Belle experiment performed the analysis of $e^+e^- \to \gamma_{ISR}\pi^+\pi^-J/\psi$ [33]. Figure 3 shows the invariant mass distribution of $\pi^+\pi^-J/\psi$, the distribution is fitted with two coherent resonances. The existence of Y(4008) state was confirmed, and the parameters of the two resonances are consistent with Belle's previous results [31]. The BaBar experiment performed the same analysis using its 454 pb^{-1} of data samples collected at $\sqrt{s}$ = 10.58 and 10.54 GeV [34], the corresponding invariant mass distribution of $\pi^+\pi^-J/\psi$ is shown in Fig. 4. The distribution is fitted with Y(4260) resonance only, and the events collected at low mass range are explained as the contribution of tail of $\psi(3686)$ and non-resonance. The disagreement on the existence of Y(4008) between two B factories need be clarify by others experiments.

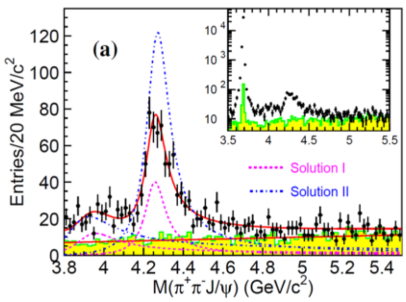

Figure 3: The invariant mass distribution of $\pi^+\pi^-J/\psi$ in the process of $e^+e^- \to \gamma_{ISR}\pi^+\pi^-J/\psi$, measured by Belle experiment, the distribution is fitted with the two coherent resonances.

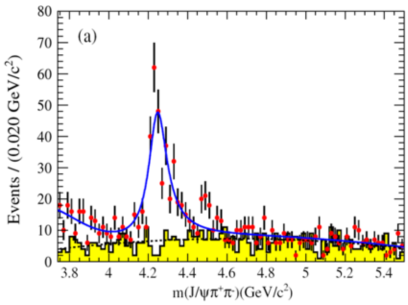

Figure 4: The invariant mass distribution of $\pi^+\pi^-J/\psi$ in the process of $e^+e^- \to \gamma_{ISR}\pi^+\pi^-J/\psi$, measured by BaBar experiment, the distribution is fitted with a Y(4260) state.

Beside via the ISR process in two B factories, the Y states can also be investigated through direct e^+e^- annihilation with CME at the corresponding energy region, the measurements have been performed by the CLEO-c and BESIII experiments. With 13.2 pb^{-1} of data sample collected at $\sqrt{s}$ = 4.26 GeV, CLEO experiment confirmed the existence of $Y(4260) \to \pi^+\pi^- J/\psi$ with 11 σ significance [35]. Also, it firstly presented the evidence of the Y(4260) decaying by a neutral dipion transition $Y(4260) \to \pi^0\pi^0 J/\psi$ with 5.1 σ significance [35]. Recently, using much higher integrate luminosity data sample, 525 fb^{-1} data collected at $\sqrt{s}$ = 4.26 GeV, BESIII experiment presented the analysis of $e^+e^- \to \pi^+\pi^- J/\psi$, the corresponding Born cross section $\sigma(e^+e^- \to \pi^+\pi^- J/\psi)$ is measured to be 62.9 ± 1.9 ± 3.7 pb [36], which is consistent very well with the BaBar and Belle's results, and with much improved precision. The data sample collected by BESIII detector around 4.26 GeV region can be use to measure the line shape of Y(4260) state, to clarify the existence of Y(4008) states.

3.2. Y states observed in $\pi^+\pi^-\psi(3686)$ final states

In the analogy process $e^+e^- \to \gamma_{ISR}\pi^+\pi^-\psi(3686)$, both BaBar and Belle experiments report the existence of Y(4360) [37, 38], while Belle experiment report the extra state of Y(4660). The existence of Y(4660) is a interesting question. Using the full 520 fb^{-1} of data samples with CM energy at or around $\Upsilon(nS)$ (n=2, 3, 4) resonances, the BaBar experiment updated the analysis of $e^+e^- \to \gamma_{ISR}\pi^+\pi^-\psi(3686)$ [39], where $\psi(3686)$ is reconstructed with its $\pi^+\pi^- J/\psi$ and $\mu^+\mu^-$ decay modes. As shown in Fig. 5, the mass distribution of $\pi^+\pi^-\psi(3686)$ exhibits clearly two structures, and is well consistent with the Belle observation. A fit with two resonances is performed on the $\pi^+\pi^-\psi(3686)$ invariant mass distribution, and the results on parameters of X(4360) and X(4660) resonances are well consistent with the previous Belle's results [38]. The existence of Y(4660) was established. Using 980 fb^{-1} data sample, Belle experiment updated the analysis of $e^+e^- \to \gamma_{ISR}\pi^+\pi^-\psi(3686)$ with the same decay modes for $\psi(3686)$ as BaBar experiment [40]. The observed distribution of $\pi^+\pi^-\psi(3686)$, as shown in Fig. 6, is consistent with that of the previous measurement. The corresponding distribution is fitted with the two coherent resonances, and the masses of two resonance are found to be 20 MeV smaller than that of the previous Belle results [38]. Since there are some events accumulated around the mass region of Y(4260), the fit with Y(4260) included is also performed, and the significance of Y(4260) is found to be 2.1 σ only, where the parameters of Y(4260) is fixed to the Belle results [33] in the fit.

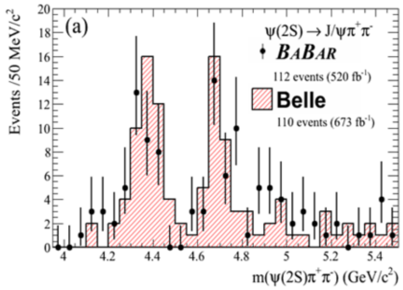

Figure 5: The invariant mass distribution of $\pi^+\pi^-\psi(3686)$ in the process of $e^+e^- \to \gamma_{ISR}\pi^+\pi^-\psi(3686)$, measured by BaBar and Belle experiments

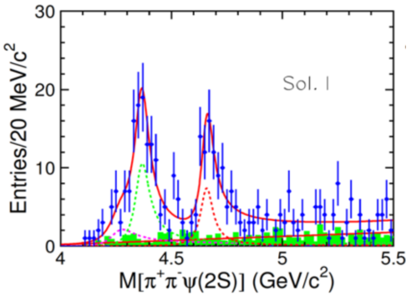

Figure 6: The invariant mass distribution of $\pi^+\pi^-\psi(3686)$ in the process of $e^+e^- \to \gamma_{ISR}\pi^+\pi^-\psi(3686)$, measured by Belle with 980 fb^{-1} data. The fit curve shows the one of four solutions of fit with three resonance.

3.3. The study of $e^+e^- \to \pi^+\pi^- h_c(1P)$ and $\omega\chi_{cJ}$

As mentioned previously, except for the dipion transition to either J/ψ or $\psi(3686)$, and the possible radiative transition of Y(4260) to X(3872) observed by BESIII experiment [23], there is not other decay mode for Y states observed experimentally to date. Searching for the new decay modes for the Y states will shed light to understand their natures.

$h_c(1P)$ is P wave spin singlet charmonium state, the observed of transitions to h_c could provide insight into the perplexing nature of the charmonium states above $D\bar{D}$ threshold [4]. It is worth to point out that various QCD calculations indicate that the charmonium hybrid lies in the mass regions of these Y states [41], and the $c\bar{c}$ tend to be in a spin-singlet state. Such a state may strongly couple to a spin-singlet charmonium state such as h_c. The significant enhancement on the cross section of the dipoin transition to h_c states was observed by CLEO experiment with data sample at $\sqrt{s}$ = 4.17 GeV [42]. The interesting question is whether the production correlated with the Y(4260) or others charmonium states. With totally 3.1 fb^{-1} of data samples collected at 13 CME spanning from 3.90

to 4.42 GeV, BESIII experiment performed the analysis of $e^+e^- \rightarrow \pi^+\pi^- h_c$ [43], where h_c is reconstructed via its electric-dipole (E1) transition to η_c, and η_c is reconstructed with 16 exclusive hadronic final states, which include about 40% of η_c decay. The measured Born cross sections of $e^+e^- \rightarrow \pi^+\pi^- h_c$ at the each CME point are shown in Fig. 7 as the filled circles with error bars, and the corresponding results from the CLEO-c are also shown as triangle with error bars in the same figure. For comparison, the Born cross sections of $e^+e^- \rightarrow \pi^+\pi^- J/\psi$ as function of CME measured by Belle experiment [33] are shown in the same plots with open circles with error bars. The measured Born cross section of $e^+e^- \rightarrow \pi^+\pi^- h_c$ is of the same order in magnitude as those of $e^+e^- \rightarrow \pi^+\pi^- J/\psi$, but with a very different line shape. There is a local maximum around 4.23 GeV observed, but in the high CME range, it is unclear if the line shape of Born cross section is a broad structure or a flat distribution. The correlation of the observed Born cross sections with Y states or others charmonium states is unclear, more data around 4.23 GeV and above 4.40 GeV may help to reveal its nature. Using the same data samples with high integral luminosity at $\sqrt{s}$ = 4.23, 4.26 and 4.36 GeV, BESIII experiment also performed the analogy neutral dipion transition $e^+e^- \rightarrow \pi^0\pi^0 h_c$, the measured cross sections are agreed with the expectation of isospin symmetry, 0.5, within 2 σ [44].

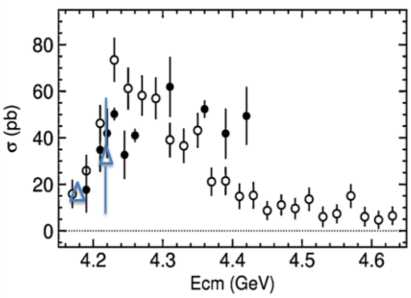

Figure 7: The Born cross section of $e^+e^- \rightarrow \pi^+\pi^- h_c$ at different CME from the BESIII (filled black circles with error bars) and CLEO-c (Triangles with error bars) experiments, as well as those of $e^+e^- \rightarrow \pi^+\pi^- J/\psi$ from Belle experiment (open circles with error bars)

Due to the threshold effect, it is expected a sizeable coupling between Y(4260) and the $\omega\chi_{c0}$ channel, which may plays a role in reducing the decay rates into open charm channels [45]. Based on the data sample at 9 CME from 4.21 to 4.42 GeV, BESIII experiment performed the analysis of $e^+e^- \rightarrow \omega\chi_{cJ}$ (J=0, 1, 2) [46]. The process $e^+e^- \rightarrow \omega\chi_{c0}$ was observed for the first time at $\sqrt{s}$ = 4.23 and 4.26 GeV, and the Born cross section are measured, respectively. The $\omega\chi_{c0}$ at the other 7 energy points and $e^+e^- \rightarrow \omega\chi_{c1}$ and $\omega\chi_{c2}$ are not significant, and the upper limits on the cross section are determined. The measured Born cross section of $e^+e^- \rightarrow \omega\chi_{c0}$ as a function of CME is shown in Fig. 8, and is found to be inconsistent with the line shape of the Y(4260) observed in $e^+e^- \rightarrow \pi^+\pi^- J/\psi$, which may indicate the production of $e^+e^- \rightarrow \omega\chi_{c0}$ does not arise from Y(4260).

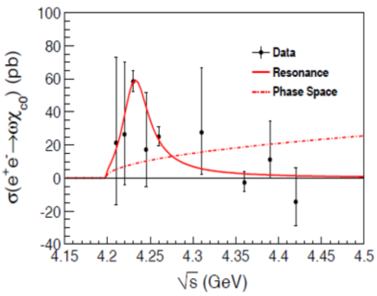

Figure 8: The Born cross section of $e^+e^- \rightarrow \omega\chi_{c0}$ at different CME points from 4.21 to 4.42 GeV

3.4. Discussion

Since most of the new Y states are produced via ISR process and observed in the dipion transition to J/ψ or $\psi(3686)$ processes, a natural interpretation of these states are the excited vector charmonium states. However, a number of peculiar features of these states reveal that these new Y states may not be conventional charmonium states. Naive quark model has been proved to describe the charmonium spectrum very well, and it expects five vector states with mass within 4.0-4.7GeV range [8] (they seen to be well established except for $5S$ state [47, 48]). However, it is found that the observed new Y states are inconsistent with quark model predictions in mass. The new observed states are all above the open charm threshold, and is expected to strongly couple to $D^{(*)}\bar{D}^{(*)}$ final states if they are the conventional charmonium states. In contrast, these states are observed in the dipion transition to low mass charmonium states only, which indicate a sizeable coupling to the charmonium final states, and absent in the $D^{(*)}\bar{D}^{(*)}X$ final states [49, 50]. Also, the states are observed neither in the exclusive hadronic final states [51] nor inclusive hadronic final states [52]. The states are not observed in the others transition to charmonium states, such as $\eta J/\psi$, either [53]. Moreover, the unexpected line shape of production cross section of $e^+e^- \rightarrow \pi^+\pi^- h_c$ and $e^+e^- \rightarrow \omega\chi_{c0}$ observed by the BESIII experiment imply the existence of the more complicate and mysterious underling dynamics in these states. Theoretically, many interpretations are proposed to classify these Y states, such as hybrid charmonium [54], tetraquark [55] or hadronic molecule [56], *etc.*, but all need further experimental inputs.

4. Z_c States

The observations of charged resonances above the open-charm threshold that couple strongly to charmonium had led to significant interest in both experimental and theoretical communities. Such resonances, decaying to a heavy charmonium state and a charged light-quark meson are manifestly exotic, requiring a minimal quark content of $Q\bar{Q}q\bar{q}$.

4.1. Observation of the $Z_c(3900)$ and $Z_c(3885)$

In the study of the $e^+e^- \to \pi^+\pi^- J/\psi$ process using a 525 pb^{-1} of data sample taken at $\sqrt{s}$ = 4.26 GeV, BESIII experiment observed a structure near 3.9 GeV/c^2, called $Z_c(3900)$, in the invariant mass of $\pi^\pm J/\psi$, $M(\pi^\pm J/\psi)$, with a statistical significance larger than 8 σ [36]. A unbinned maximum likelihood fit to the distribution of $M(\pi^\pm J/\psi)$ is performed, as shown in Fig. 9, and the mass and width of Z_c are found to be 3899.0 ± 3.6 ± 4.9 MeV/c^2 and 46 ± 10 ± 20 MeV, respectively, its production ratio was measured to be $R = \frac{e^+e^-\to\pi^\pm Z_c^\mp(3900)\to\pi^+\pi^- J/\psi}{e^+e^-\to\pi^+\pi^- J/\psi}$. = (21.5 ± 3.3 ± 7.5)%

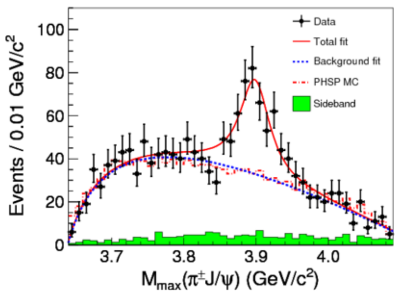

Figure 9: The distribution of $M(\pi J/\psi)$ from BESIII experiment, and its corresponding fit curve

Using ISR method, Belle experiment measured the cross section of $e^+e^- \to \pi^+\pi^- J/\psi$ from 3.8 to 5.5 GeV/c^2, a intermediate state, $Z_c(3900)$, was observed in the invariant mass of $\pi^\pm J/\psi$ for the events with the invariant mass of $\pi^+\pi^- J/\psi$ around Y(4260) [33]. The distribution of the invariant mass of $\pi^\pm J/\psi$ is shown in Fig. 10. A unbined likelihood fit results in the mass and width are 3894 ± 6.6 ± 4.5 MeV/c^2 and 63 ± 24 ± 26 MeV, respectively, and the corresponding statistics significance of $Z_c(3900)$ is large than 5.2 σ.

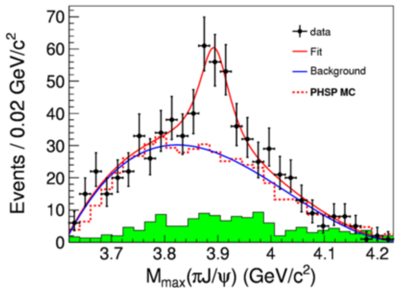

Figure 10: The distribution of $M(\pi J/\psi)$ from Belle experiment, and its corresponding fit curve

The $Z_c(3900)$ was also confirmed shortly after with CLEO-c data at $\sqrt{s}$ = 4.17 GeV [57], whose mass and width are consistent with the BESIII and Belle measurements. $Z_c(3900)$ is the first charged charmoniumlike particle observed by the more than two different experiments.

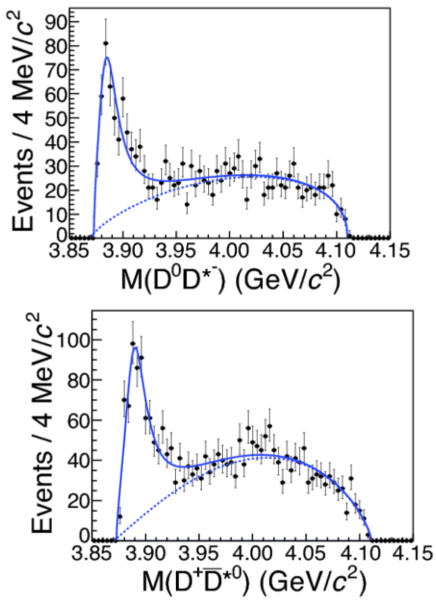

Figure 11: The invariant mass distributions of D^0D^{*-} and D^+D^{*0} from Belle experiment, and its corresponding fit curve

Since the new observed $Z_c(3900)$ is very close to the theshold of $(D\bar{D}^*)^\pm$ in mass, it is interesting to known its coupling to the $(D\bar{D}^*)^\pm$ final states. Using the same data sample at $\sqrt{s}$ = 4.26 GeV, BESIII experiment performed the study of $e^+e^- \to \pi^\pm(D\bar{D}^* + c.c.)^\mp$ [58]. To increase the detection efficiency, a partial reconstruction technique was applied, *i.e.* only the bachelor $\pi^\pm$ and one

D meson were detected, and the D^{0*} was reconstructed by the recoiling mass of $D\pi^{\pm}$ under the energy momentum conservation. As shown in Fig. 11, a charged structure, named $Z_c(3885)$, was observed on the invariant mass distribution of $(D\bar{D}^*)^{\pm}$ near the $(D\bar{D}^*)^{\pm}$ mass threshold. A unbinned likelihood fit on the $(D\bar{D}^*)^{\pm}$ invariant mass was performed, and results in the mass and width are $3883.9\pm1.5\pm4.2$ MeV/c^2 and $24.8\pm3.3\pm11.0$ MeV, respectively. The pole angular distribution of bachelor $\pi^{\pm}$, shown in Fig. 12, favors its quantum number to be 1^+ assignment.

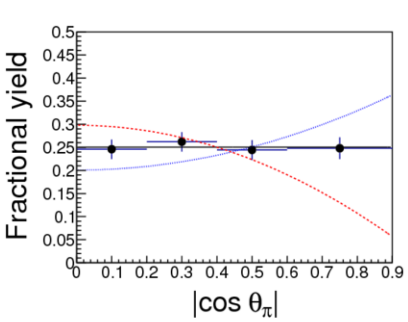

Figure 12: The pole angular distribution of bachelor $\pi^{\pm}$, the solid, dashed and dotted curves show expectations for $J^P = 1^+, 0^-, 1^-$, respectively.

An important question is whether the $Z_c(3885)$ and $Z_c(3900)$ are the same particle. The mass and width of $Z_c(3885)$ are 2 σ and 1 σ, respectively, lower than those of $Z_c(3900)$ observed by BESIII and Belle experiments. However, neither experiment performed the fit considering the interference with a coherent non-resonant background that could shift the results. A quantum number study of $Z_c(3900)$ would provide an additional test of this question. Assuming the $Z_c(3885)$ and $Z_c(3900)$ are the same particle, we can get the $\frac{\Gamma(Z_c(3885)\to D\bar{D}^*)}{Z_c(3900)\to\pi J/\psi} = 6.2 \pm 1.1 \pm 2.7$. The ratio is much smaller than the typical values for the decays of conventional charmonium states above the open charm threshold (a few hundred [59] normally), which suggest the influence of very different dynamics between Y(4260) and $Z_c(3900)$.

Another important question for $Z_c(3900)$ is if its isospin partner $Z_c(3900)^0$, which is expected to couple to $\pi^0 J/\psi$ final state, is existed. CLEO-c data at $\sqrt{s}$ = 4.17GeV show the evidence of $Z_c(3900)^0$ with statistical significance 3.5 σ in the process $e^+e^- \to \pi^0\pi^0 J/\psi$ [57]. Using 2.8fb^{-1} data at 10 CME points from 4230 to 4420 MeV, BESIII experiment performed the study of $e^+e^- \to \pi^0\pi^0 J/\psi$, the preliminary results show $Z_c(3900)^0$ signal at $\sqrt{s}$ = 4.23, 4.26 and 4.36 GeV data samples with statistical significance 10.4 σ, and the corresponding mass and width are 3894.8 ± 2.3 MeV/c^2 and 29.6 ± 8.2 MeV, respectively, which are very close to those of charged $Z_c(3900)$. The nature of isospin vector is established for $Z_c(3900)$.

4.2. Observation of the $Z_c(4020)$ and $Z_c(4025)$

As described in Sec.3, BESIII experiments measured the $e^+e^- \to \pi^+\pi^- h_c$ cross section at CME between 3.90 and 4.42 GeV [43]. The intermediate states are studied by examining the Dalitz plot of the selected $\pi^+\pi^- h_c$ candidate events with the data sample at $\sqrt{s}$=4.23, 4.26 and 4.36 GeV, which have large luminosity. There are not clear structures observed in the $\pi^+\pi^-$ system, while a distinct structure, called $Z_c(4020)$, was observed around 4.02 GeV/c^2 in the $\pi^{\pm}h_c$ system in the Dalitz plot, no significant $Z_c(3900)$ signal is observed. Figure 13 shows the corresponding distribution of invariant mass of $\pi^{\pm}h_c$, $M(\pi^{\pm}h_c)$ (two entries per event), as well as the background events estimated from normalized h_c mass sideband. The unbinned maximum likelihood fit is performed to the invariant mass spectrum of $\pi^{\pm}h_c$, which neglect possible interferences, results in a mass of $4022.9 \pm 0.8 \pm 2.7$ MeV/c^2 and a width of $7.9 \pm 2.7 \pm 2.6$ MeV and with a statistical significance greater than 8.9 σ for $Z_c(4020)$ signal. The unbinned maximum likelihood fit includes $Z_c(3900)$ and $Z_c(4020)$ is also performed, results in a statistical significance of 2.1 σ for $Z_c(3900)$.

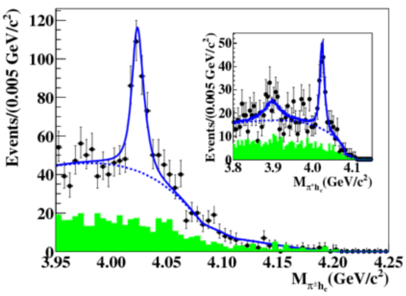

Figure 13: The distribution of invariant mass of $\pi^{\pm}h_c$ from BESIII experiment, (sum of the data sample at $\sqrt{s}$ = 4.23, 4.26, and 4.36GeV), the curve shows the fit results with $Z_c(4020)$ included. The inset shows the distribution of invariant mass of π^+h_c, and fit results with the $Z_c(3900)$ and $Z_c(4020)$ included.

Since the mass of $Z_c(4020)$ is very closed to the $(D^*\bar{D}^*)^{\pm}$ mass threshold, it is interesting to know if it couples to $(D^*\bar{D}^*)^{\pm}$ final state. BESIII experiment performed a study of $e^+e^- \to (D^*\bar{D}^*)^{\pm}\pi^{\mp}$ process using 827 pb^{-1} data at 4.26 GeV [60]. A partial reconstruction technique, *i.e.*, only the charged D meson and the bachelor pion were reconstructed, is applied to increase the detection efficiency, and a additional π^0 in final states is required to further suppress the backgrounds. The recoiling mass spectrum of the bachelor $\pi^\pm$ is shown in Fig. 14, a structure near the $(D^*\bar{D}^*)^\pm$ threshold is observed, which can not be described with the phase space. A unbinned maximum likelihood method yields a mass of 4026.3 ± 2.6 ± 3.7 MeV/c^2 and a width of 24.8 ± 5.6 ± 7.7 MeV. The measured mass and width agree with those of the $Z_c(4020)$ within 1.5 σ. Assuming the $Z_c(4020)$ and $Z_c(4025)$ are the same state, the ratio of partial decay widths is determined to be $\frac{Z_c(4025)\to(D^*\bar{D}^*)^\pm}{Z_c(4020)\to\pi\psi(3686)} = 12 \pm 5$, which is much smaller than the expectation of the conventional charmonium state above open charm pair mass threshold.

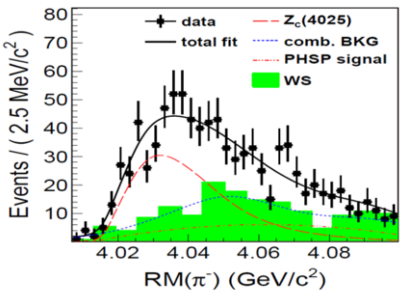

Figure 14: The recoiling mass of $\pi^\pm$ from BESIII experiment in the process of $e^+e^- \to (D^*\bar{D}^*)^\pm\pi^\mp$, the curve shows the fit results with $Z_c(4025)$ included.

The same as $Z_c(3900)$, it is also interesting to search for the isovector partner of $Z_c(4020)$, neutral $Z_c(4020)^0$ state. BESIII experiment performed the analysis for analogy process $e^+e^- \to \pi^0\pi^0 h_c$ with data sample at $\sqrt{s}$ = 4.23, 4.26 and 4.36 GeV [44]. A obvious peak around 4.02 GeV/c^2 was observed in the $\pi^0 h_c$ invariant mass spectrum, as shown in Fig. 15, a simultaneous fit to the $\pi^0 h_c$ mass in the three CME points with a fixed width of $Z_c(4020)$ is performed, yields a mass of 4023.6±2.2±3.9 MeV/c^2 and a statistical significance larger than 5 σ for $Z_c(4020)^0$. The nature of isospin vector is established for $Z_c(4020)$.

4.3. *The confirmation of* $Z_c(4430)$ *and observation of* $Z_c(4200)$

The first evidence of charged charmoniumlike particle, named $Z_c(4430)$, was reported by Belle collaboration in the $\pi^\pm\psi(3686)$ final state in the decay $B \to K\pi^\pm\psi(3686)$ with significance 6.5 σ. The analysis is based on 605 fb^{-1} of data sample collected near the $\Upsilon(4S)$ resonance [61]. However, based on 413 fb^{-1} of data sample collection at $\sqrt{s}$ = 10.58 GeV, BaBar experiment did not support the existence of $Z_c(4430)$ in the same process by a two dimensional (2D) analysis,

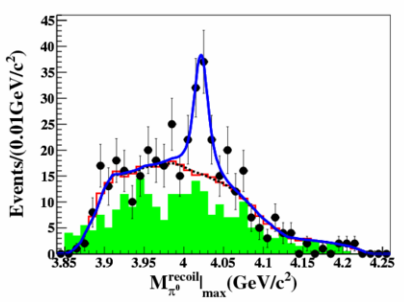

Figure 15: The distribution of invariant mass of $\pi^0 h_c$ from BESIII experiment, (sum of the data sample at $\sqrt{s}$ = 4.23, 4.26, and 4.36GeV), the curve shows the fit results with $Z_c(4020)$ included.

where the invariant mass distribution of $\pi^\pm\psi(3686)$ can be well explained by the reflection of the K^* in $K\pi$ final state [62]. With the similar 2D analysis method, which take into account the effect of K^* reflections, Belle updated the analysis with 605 fb^{-1} of data sample [63], and confirm the existence of $Z_c(4430)$ with 6.4 σ. Recently, base on 711 fb^{-1} data sample, Belle collaboration further updated the study with a full 4D amplitude analysis, confirmed the existence of $Z_c(4430)$ [64], and the preferred assignment of its quantum number 1^+ is favoured over the other assignment by more than 3.4 σ. The results for the mass and width of $Z_c(4430)$ are 50 MeV(/c^2) higher and much broad than the previously results [61], respectively. Figure 16 shows the distribution of $M^2(\pi\psi(3686))$ from Belle experiments, and its corresponding fit curve from the full 4D amplitude analysis.

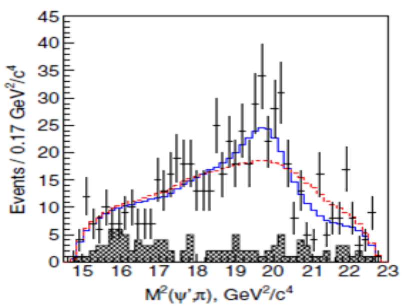

Figure 16: The distribution of $M^2(\pi\psi(3686))$ from Belle experiment, and its corresponding fit curve from the full 4D amplitude analysis

The existence of the $Z_c(4430)$ has been questioned until recently the LHCb experiment reported a full 4D model-dependent amplitude fit to a much larger sample of $B^0 \to K^+\pi^-\psi(3686)$ event [65], where all known $K^{*0} \to K^+\pi^-$ resonance below or near the mass threshold are included in the fit with theirs nominal mass. The $Z_c(4430)$ was observed with a significance larger than 13.9 σ, the spin-parity is determined to be 1^+, and the mass and width are consistent with those of Belle latest results. Figure 17 shows the distribution of $M^2(\pi\psi(3686))$ from LHCb experiments, and its corresponding fit curve from the full 4D amplitude analysis. With the large statistics, LHCb experiment also divided the $M^2(\pi\psi(3686))$ bins around the $Z_c(4430)$ peak and fit the real and imaginary parties of $Z_c(4430)$ amplitudes, the resulting Argand diagram is consistent with a rapid changed of the $Z_c(4430)$ phase when its magnitude reached the maximum, a behavior characteristic of a resonance. With the LHCb results, the first charged charmoniumlike state, $Z_c(4430)$, is established after the seven years of its discovery at Belle experiment, though its mass and width are changed.

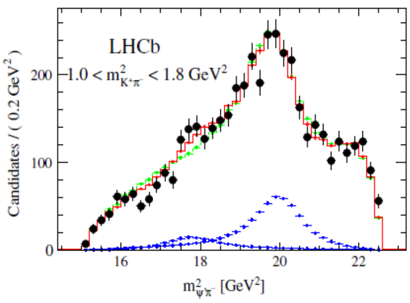

Figure 17: The distribution of $M^2(\pi\psi(3686))$ from LHCb experiment, and its corresponding fit curve from the full 4-D amplitude analysis

With the similar full 4D analysis method, Belle collaboration performed the study on analogy process $B^0 \to K^-\pi^+J/\psi$ based on the same 711 fb^{-1} of data sample near the $\Upsilon(4S)$ resonance, where all the known excited K^*s below and near the threshold are included in the fit. A resonance, around 4200MeV/c^2 with very broad width (~370MeV), named $Z_c(4200)$, is found with 7.2 σ significance. The quantum number prefer 1^+, and the other assignments are rule out with at least 5.6 σ level. The existence of $Z_c(4200)$ state need to be confirmed by other experiments. In addition, a strong evidence for $Z_c(4430)^- \to \pi^- J/\psi$ is observed with a significance level of more than 4.0 σ. It is the second decay mode of $Z_c(4430)$ and the $R = \frac{B(Z_c(4430)^- \to \pi^- J/\psi)}{B(Z_c(4430)^- \to \pi^- \psi(3686))} = 0.09^{+0.18}_{-0.05}$, which is a very important variable to distinguish the nature of $Z_c(4430)$ state.

4.4. Discussions

To date, there are three charged charmoniumlike states, $Z_c(3900)$, $Z_c(4020)$ and $Z_c(4430)$ are established experimentally, while others two states $Z_c(4050)$ and $Z_c(4250)$ observed in $B \to K\chi_{c1}\pi^-$[66] and $Z_c(4200)$ observed in $B^0 \to K^+\pi^-J/\psi$ by Belle experiment need further confirmation by other experiments.

The nature of these states are unclear, and have been discussed for a long time. We have not conclude if they are the new type of QCD states or due to dynamically generated structures, but it is sure they are not the conventional charmonium. Many interpretation have been proposed [4] to explain these states, but all need more experimental input. The understanding of these Z_c states and the similar states in the $b\bar{b}$ system [67] may help in the development of the QCD at non-perturbative domain.

5. Summarry and perspectives

QCD predicts the existence of exotic states, searching for the exotic states is a directly test of QCD. In the past decade, a lots of new charmoniumlike states are observed in charmonium mass region from different experiment, but their peculiar features reveal an exotic nature which excludes a conventional charmonium interpretation. The nature of these new observations are unclear to date. More experimental inputs, *e.g.* measurement of more transitions between states, exploration of all possible production and decay mechanisms, precisely measurement of their properties and strong similarities between charmonium and bottomonium system, may shed light in understand their natures. The past Belle, BaBar, CLEO-c and the running BESIII experiments have remarkable success and significant contribution on these studies, and can immediately add our understanding for these new observations. The coming experiments, Belle-II, Panda, upgraded LHC and others experiments, such as CLAS12, GlueX *etc*, are definitely believed to have much more fruitful results in future.

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